AD-A127 612 USE OF INDUCED SPATIAL INCOHERENCE FOR UNIFORM ILLUMINATION ON LASER FUSION TARGETS(U) NAVAL RESEARCH LAB WASHINGTON DC R H LEHMBERG ET AL. 11 APR 83 1/1

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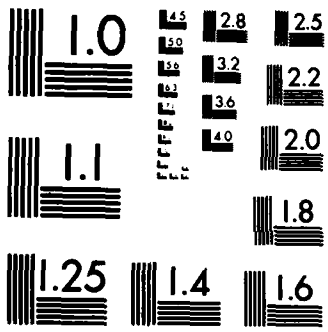

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER NRL Memorandum Report 5029	2. GOVT ACCESSION NO. AD A127612	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) USE OF INDUCED SPATIAL INCOHERENCE FOR UNIFORM ILLUMINATION OF LASER FUSION TARGETS		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) R. H. Lehmberg and S. P. Obenschain		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, DC 20375		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS DOE AI08-79DP 40092(172) 47-0859-0-3
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Department of Energy Washington, DC 20545		12. REPORT DATE April 11, 1983 13. NUMBER OF PAGES 13
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Uniform illumination
Spatial incoherence
Echelon
Temporal averaging

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

We report a technique to achieve very uniform illumination of laser irradiated targets by inducing a controlled amount of transverse spatial incoherence in the output beam of a broadband laser. The spatial incoherence is created by imposing different optical delays upon different transverse sections of the beam, and choosing the delay increments to be larger than the laser coherence time $t_c = 1/\Delta\nu$. This technique may allow easy attainment of the pellet illumination uniformity required for laser fusion.

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USE OF INDUCED SPATIAL INCOHERENCE FOR UNIFORM ILLUMINATION OF LASER FUSION TARGETS

High gain laser fusion requires a very uniform ablation pressure at the pellet surface.[1,2] For the case of directly illuminated pellets, this in turn requires a high degree of uniformity in the incident intensity. Even at $\lambda = 1\ \mu m$, where significant lateral smoothing can take place in the ablating plasma,[3,4] illumination uniformities to within $\pm 10\%$ are likely to be required. At shorter wavelengths, where the smaller absorption-ablation distance of the plasma provides only minimal lateral smoothing,[4] illumination uniformities to within $\pm 1\%$ may be required.

Efforts to achieve uniform illumination have been frustrated by imperfections in the high power laser systems. The cumulative effect of small phase aberrations (both linear and nonlinear) introduced by each optical element of a multistage laser produces large random intensity nonuniformities at the output, and these can only be partially controlled at great expense by using ultra high quality optics and extensive beam relaying.[5] In order to obtain the desired intensity and focal diameter with a lens of reasonable focal length, one normally places the pellet in the quasi near field of the lens, rather than at best focus. With this configuration, however, the nonuniformities at the laser output tend to be mapped onto the pellet. Random nonuniformities may be statistically smoothed by overlapping many independent beams at the pellet, but the large number of beam lines required to do this in a conventional way may be prohibitive.

In this letter, we report a simple and novel technique that allows a high degree of illumination uniformity with modest quality laser beams. This technique induces a controlled amount of transverse spatial incoherence in the output beam of a broadband laser, whose coherence time $t_c = 1/\Delta\nu$ is short in comparison to the pulsewidth t_p. The spatial incoherence is achieved by imposing different optical delays upon different transverse sections of the beam, and choosing the delay increments to be larger than t_c. A wide aperture beam is thus broken up into a large number N of independent beamlets. At the focus of a lens, these overlap to produce a complicated interference pattern modulated by a smooth envelope that characterizes the diffraction of an individual beamlet. On time scales long in comparison to t_c, the interference pattern averages out, leaving only the smooth diffraction profile. The pellet will effectively ignore the rapidly shifting interference pattern if its hydrodynamic response time t_h satisfies $t_h >> t_c$. The diffraction profile is relatively insensitive to amplitude and phase nonuniformities in the incident beam; in fact, the beam need only be approximately uniform over the small width of each beamlet. We estimate that laser bandwidths as small as 0.2% should be adequate to implement this scheme for laser fusion.

The concept described here bears some similarity to a technique recently proposed by Mima and Kato,[6] in which the beam is broken up by a random phase mask. In that proposal, however, the random phase relationship among the beamlets would remain fixed in time; i.e., the incident beam becomes aberrated, but not really incoherent. The focal interference pattern therefore persists throughout the pulse, and it invariably contains longer scalelength components that would be deleterious to the pellet implosion uniformity. Similar considerations apply to optical beam integrating devices that are designed to produce a "top hat" spatial profile.[7]

Manuscript approved January 27, 1983.

The induced incoherence concept is illustrated for one transverse dimension in Fig. 1. The incident laser beam amplitude is

$$E_L(x,z,t) = A(x)F(t - z/c) \exp[-i\omega(t - z/c)], \tag{1}$$

where the complex amplitudes $A(x)$ and $F(t)$ describe the transverse nonuniformities and slow time dependence, respectively. For a Q-switched pulse in a broad bandpass laser medium, $F(t)$ can be approximated by a quasi-stationary stochastic variable satisfying Gaussian statistics. The correlation function $<F(t)F^*(t + \tau)>$ will exhibit a smooth localized τ dependence of width $t_c = 2\pi/\Delta\omega$, so that $<F(t)F^*(t + \tau)> \simeq 0$ for $|\tau| > t_c$, while the mean square amplitude $<|F(t)|^2>$ varies negligibly within interval t_c if $t_c << t_p$. (Here, the brackets denote an ensemble average.) This beam propagates through the transparent echelon structure, which introduces time delays t_n that increase with each step. If the beam is nearly uniform over scalelength D_1 (i.e., if $|\partial A/\partial x|D_1 << |A|$), then the output field is approximately

$$\sum_{n=1}^{N} \epsilon(x - nD_1)A_n F(t - t_n) \exp[i\omega(t_n - t)], \tag{2}$$

where $A_n \equiv A(nD_1)$, and $\epsilon(x)$ is a "top hat" function equal to unity for $|x| \leqslant D_1/2$ and zero elsewhere. Without loss of generality, one can normalize the amplitudes so that $\Sigma_n|A_n|^2 = 1$. To produce nearly complete transverse spatial incoherence within times of order t_c, the delay increments $t_{n+1} - t_n$ must be larger than t_c, and ωt_n must vary randomly (over at least 2π) from step to step. The latter requirement ensures that phase relationships among nearby beamlets will not be duplicated among lower beamlets as the emerging wavefront shears its way down the echelon.

In the focal plane of the lens, the instantaneous intensity profile $I(x,t) = |E_f(x,t)|^2$ of the overlapping beamlets is

$$I(x,t) = C \,\mathrm{sinc}\left(\frac{2\pi x}{d}\right) \sum_{m=1-N}^{N-1} J_m(t) \exp\left(i\frac{2\pi x}{\Lambda_m}\right), \tag{3}$$

where $\mathrm{sinc}\,(2\pi x/d) = \sin^2(2\pi x/d)/(2\pi x/d)^2$ is the diffraction envelope of width $d = 2\lambda f/D_1$ (zero-to-zero), $C \equiv D_1^2/f\lambda$, $\Lambda_m = \lambda f/m\,D_1$ is the mth transverse mode wavelength, and

$$J_m(t) = \sum_n A_n A^*_{n+m}\, F(t - t_n)F^*(t - t_{n+m}) \exp[i\omega(t_n - t_{n+m})] \tag{4}$$

is the mth transverse mode amplitude, assuming for simplicity that the maximum delay time difference satisfies $t_N - t_1 << t_p$. The spatial profile of $I(x,t)$ is generally a complicated random pattern, as shown on the right hand side of Fig. 1. If $t_c > t_N - t_1$; then the beamlets remain coherent (although randomly phased), and this pattern will persist throughout the pulse. This corresponds to the case discussed in Ref. (6). If $t_c < t_{n+1} - t_n$, however, the beamlets become effectively incoherent with respect to one another, and the pattern averages out in times $T >> t_c$. The time-average intensity $\bar{I}(x,t,T)$ over interval $(t,t + T)$ thus approaches the ensemble average value

$$<I(x,t)> = C<|F(t)|^2> \mathrm{sinc}\,(2\pi x/d) \tag{5}$$

when $t_c << T << t_p$. This spatial profile, which is indicated by the smooth curve in Fig. 1, contains over 90% of the energy in its central lobe $|x| \leqslant d/2$. As a numerical example, let $\lambda = 1\,\mu$m, $f = 5$ m, and $D_1 = 5$ mm; then $d = 2$ mm.

To estimate the residual random nonuniformities of $\bar{I}(x,t,T)$, we examine the ensemble fluctuations in the time-averaged mode amplitudes $\bar{J}_m(t,T)$ for $m \neq 0$. Since $<\bar{J}_m(t,T)> = \delta_{m,0}<|F(t)|^2>$, the relative magnitude of the RMS energy fluctuations in all off-axis modes up to $|m| = M \leqslant N - 1$ is given by the ratio

$$R_M = \left[\sum_{|m|=1}^{M} <|J_m(t,T)|^2>\right]^{1/2} / <J_0(t,T)> \tag{6a}$$

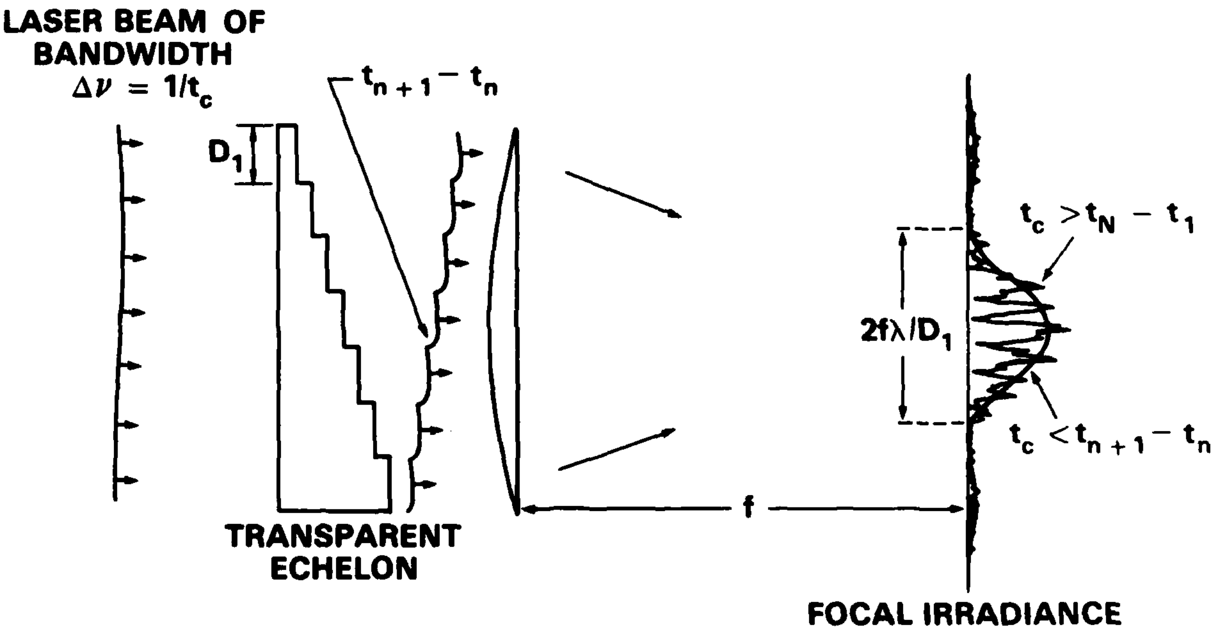

Fig. 1 — Use of spatial incoherence induced by a transparent echelon to smooth the focal spot irradiance of a broadband laser.

$$= \bar{\gamma} \left(\frac{t_c}{T} \right)^{1/2} \left[\sum_{|m|=1}^{M} \sum_{n} |A_n|^2 |A_{n+m}|^2 \right]^{1/2}, \tag{6b}$$

where $T >> t_c$, and

$$\bar{\gamma}^2 = \int_{-\infty}^{\infty} \left| \frac{<F(t)F^*(t+\tau)>}{<|F(t)|^2>} \right|^2 \frac{d\tau}{t_c} \lesssim 1. \tag{7}$$

In deriving expression (6b), we have assumed Gaussian statistics for $F(t)$ and random phases for ωt_n. Expression (6b) reduces to $\bar{\gamma}(t_c/T)^{1/2}$ when $M = N - 1$; however, for laser fusion, the most dangerous off-axis modes are those with long transverse wavelengths $|\Lambda_m| > \Lambda_M = d/2M$ where $M < N - 1$, and Λ_M is comparable to the absorption-ablation distance in the ablating plasma.[1-3] If $M << N - 1$, then the n summation in (6b) can be approximated by $N(1/N^2)$, and

$$R_M \simeq \bar{\gamma} (t_c/T)^{1/2} (d/N\Lambda_M)^{1/2}. \tag{8}$$

The concepts introduced here can be extended to two transverse dimensions in any one of several ways, such as the use of two perpendicular echelons, or a structure in which the steps consist of squares, closely packed hexagonals, or concentric circles. If two perpendicular echelons are used, the time delay increments on the second one should be as large as the total $t_N - t_1$ on the first. The average intensity at focus then becomes proportional to sinc $(2\pi x/d)$ sinc $(2\pi y/d)$ (which contains 82% of the energy in the center lobes), while expression (8) becomes

$$R_M \simeq \bar{\gamma} (t_c/T)^{1/2} \pi^{1/2} d/2N\Lambda_M. \tag{9}$$

From expressions (8) and (9), we see that two factors contribute to the beam smoothing. The $d/N\Lambda_M$ term arises because part of the energy has been channeled into (presumably) less dangerous modes at shorter transverse wavelengths. This is the smoothing mechanism proposed in Ref. (6). For a pellet of diameter d, a maximum allowable Λ_M of $d/10$, and $N = 40$ steps in each echelon, one obtains $d/N\Lambda_M = 1/4$. The $(t_c/T)^{1/2}$ term (which suppresses *all* off-axis modes) arises from the temporal averaging, where T/t_c represents the effective number of independent random intensity distributions contributing to the irradiance within interval T. For $t_c \sim 1$ psec and an averaging time $T = 400$ psec, this factor alone will effect a 20-fold reduction of R_M.

The use of induced incoherence for beam smoothing was tested with a transparent echelon-lens combination similar to the one shown in Fig. 1. A laser beam of variable coherence time is produced by an actively Q-switched Nd-glass oscillator. The oscillator bandwidth, which is monitored by a spectrograph, is adjusted by intracavity etalons, and by varying the gain to loss ratio in the cavity. Pulsewidths are typically 30 nsec. The beam from the oscillator is expanded to a 20 mm diameter and transmitted through the echelon, which consists of overlapped 1 mm thick glass slides cemented together to minimize losses. This echelon breaks the beam into ~1 mm wide beamlets with a 1.7 psec delay increment between adjacent beamlets. The beamlets then pass through a slit perpendicular to the echelon steps to achieve a one-dimensional geometry, and are focused onto a Vidicon camera by a 1 meter focal length lens. The vidicon measures the focal profile averaged over the laser pulsewidth.

Figure 2 shows the effect of the echelon on the focal distribution with a narrow band HeNe laser in place of the glass oscillator. The echelon broadens the focus due to diffraction, and produces a complicated pattern due to interference among the coherent beamlets.

Figure 3 shows the focal distributions with the echelon and the variable bandwidth glass oscillator. When the laser is adjusted for a narrow bandwidth, one obtains a complicated interference pattern, as with the HeNe laser. At the intermediate bandwidth shown, the coherence time $t_c = 1/\Delta\nu \approx 4.6$ psec is longer than the delay between nearby beamlets, but shorter than that of the widely spaced beamlets. Here the shorter scalelength interference pattern produced by the widely spaced beamlets (that intersect

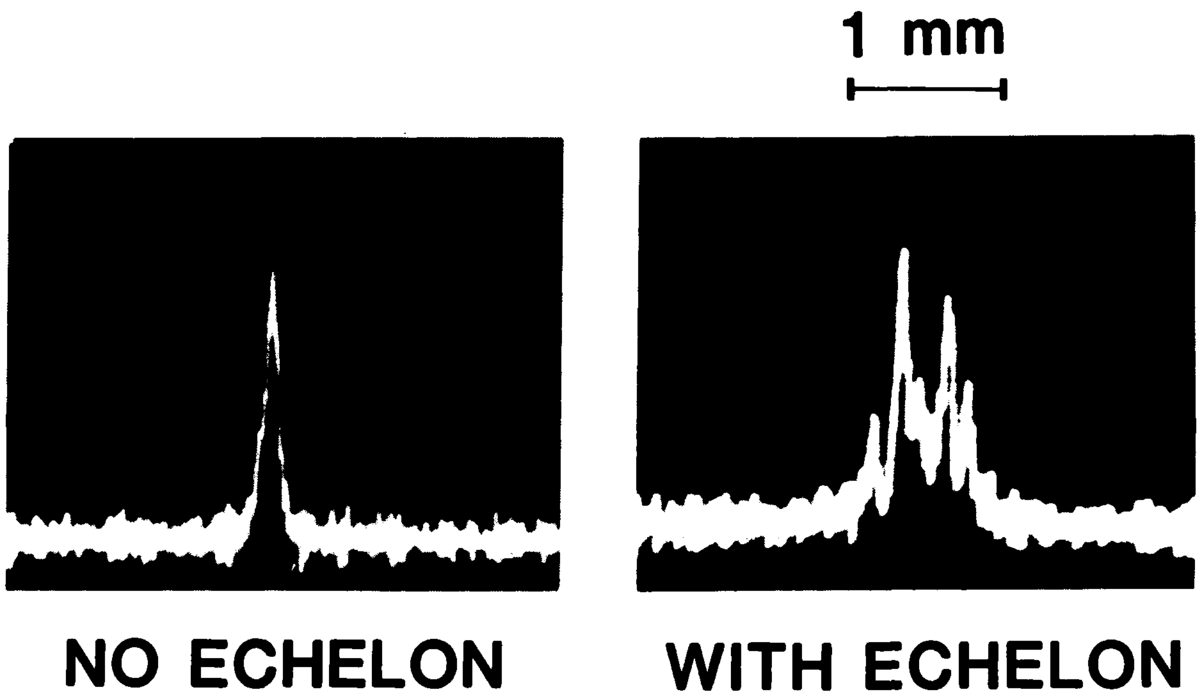

Fig. 2 — Far-field focal profiles obtained using a HeNe laser with and without the echelon. The vidicon camera employed for the measurements has a 25 μm spatial resolution.

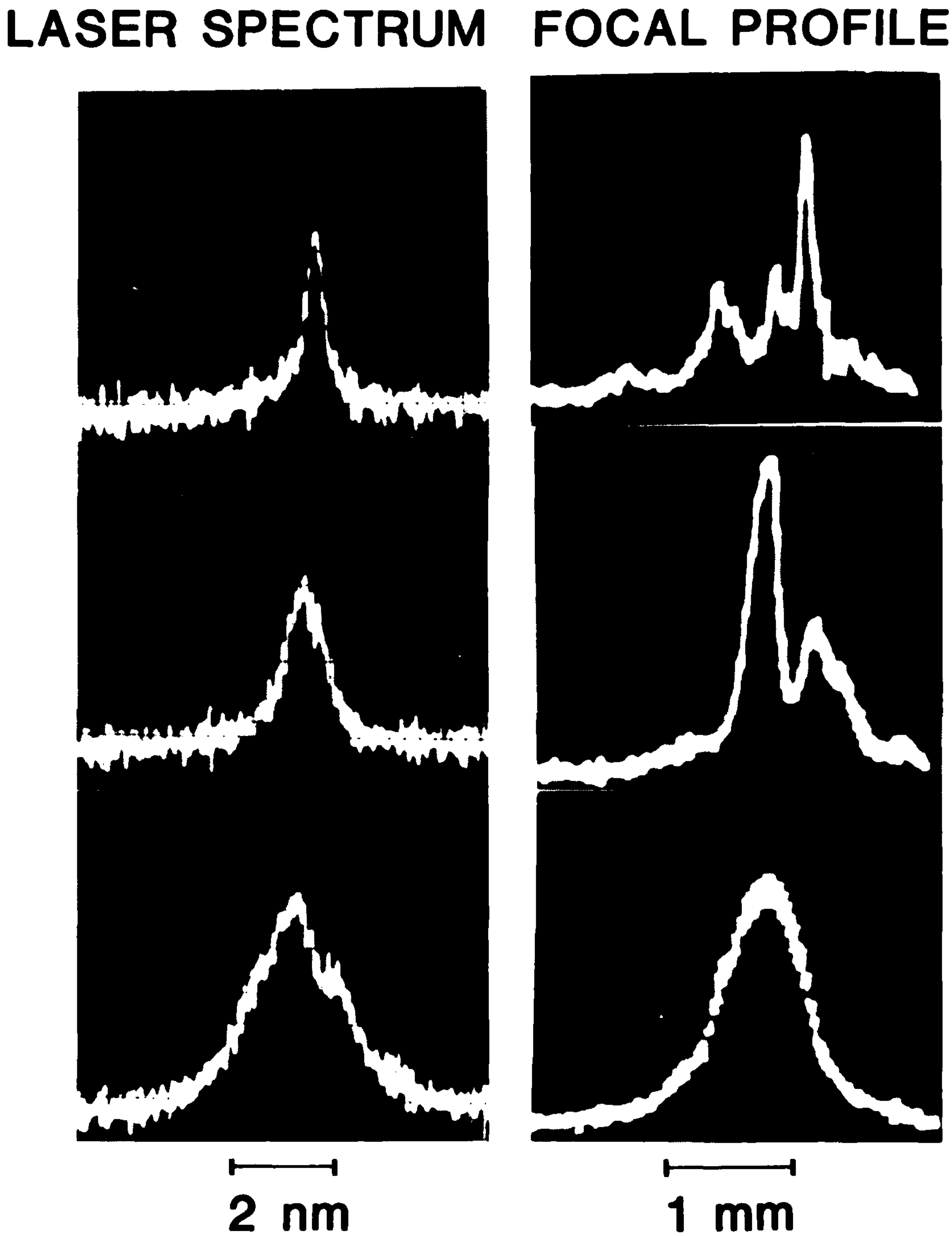

Fig. 3 — Far-field focal profiles obtained with the echelon as the bandwidth of the glass oscillator is varied.

at larger angles) is smoothed, while the longer scalelength pattern produced by adjacent beamlets persists. Finally, when t_c becomes short enough (~ 1.6 psec for the case shown) the interference among adjacent beamlets averages out, and one obtains the smooth focal distribution shown.

We have also tested the ability of the induced incoherence technique to smooth out nonuniformity in the incident laser beam. Figure 4(a) shows the illumination obtained in the quasi-near field (2.5 cm closer to the lens than best focus) when a large amplitude nonuniformity was impressed on the incident laser beam without the echelon. In Fig. 4(b), where the echelon has been inserted in the beam, the nonuniformity is eliminated. The temporal incoherence of the laser was the same in both cases. The echelon was found to provide a significant smoothing effect over a distance $\pm\Delta z$ (from best focus) given by $\Delta z \simeq d/\theta$, where θ is the convergence angle of the outermost beamlets.

The induced incoherence smoothing technique is applicable to high power glass laser systems. In measurements of gain vs. wavelength, we found the gain coefficient for phosphate glass (Q-98), to be within 97% of the peak value over the 0.2% bandwidth used in these experiments. Thus, with a modest increase in the gain, a high power system could accommodate the bandwidths used in the above experiments. Other lasers, such as KrF, with similar bandwidth capabilities should also be applicable to the technique.

The smallest laser bandwidth that can be used will be determined by the required number of beamlets N^2 and the pulsewidth t_p. The delay increment of the echelon ($t_{n+1} - t_n > t_c$) limits the risetime at focus to $\gtrsim N^2 t_c$; hence, for $N^2 \simeq 1000$ and $t_c \simeq 1$ psec, the total delay across the beam would be $\gtrsim 1$ nsec. Since fusion reactor pellets will involve pulsewidths >10 nsec, this should not be a serious restriction. Aside from this consideration, a lower bound on $\Delta\nu$ may be determined by the onset of plasma instabilities produced in the interference intensity maxima. At high irradiances, this may require that t_c be less than the instability growth time.

In this paper, we have demonstrated both theoretically and experimentally the use of programmed spatial incoherence to achieve a smooth illumination profile on flat targets. This technique has a marked advantage over other techniques involving a coherent laser, such as the random phase plate or the Spawr integrator, in that (1) virtually unlimited degrees of uniformity can be achieved, and (2) the focal spot irradiance is uniform even on short spatial scalelengths. The second feature may be important for avoiding instabilities in laser plasma interactions, such as small scale self-focusing and stimulated Brillouin scattering. For the fusion application, one needs uniform illumination of a spherical surface. Earlier studies have shown that if the incident laser profiles are smooth, one can achieve uniform illumination of a spherical surface by overlapping a relatively small ($\gtrsim 20$) number of beams.[8-11] The problem prior to the availability of this technique has been in achieving a smooth and reproducible focal profile in a single beam.

The smoothing technique appears highly promising for the fusion application. It should also be applicable to other processes, such as shock wave generation, which require uniform illumination by a concentrated laser beam.

We gratefully acknowledge the valuable discussions and suggestions by Dr. S. E. Bodner, and the technical assistance of M. Fink, J. Kosakowski, H. Hellfeld and N. Nocerino. This work was supported jointly by the Office of Naval Research and the U.S. Department of Energy.

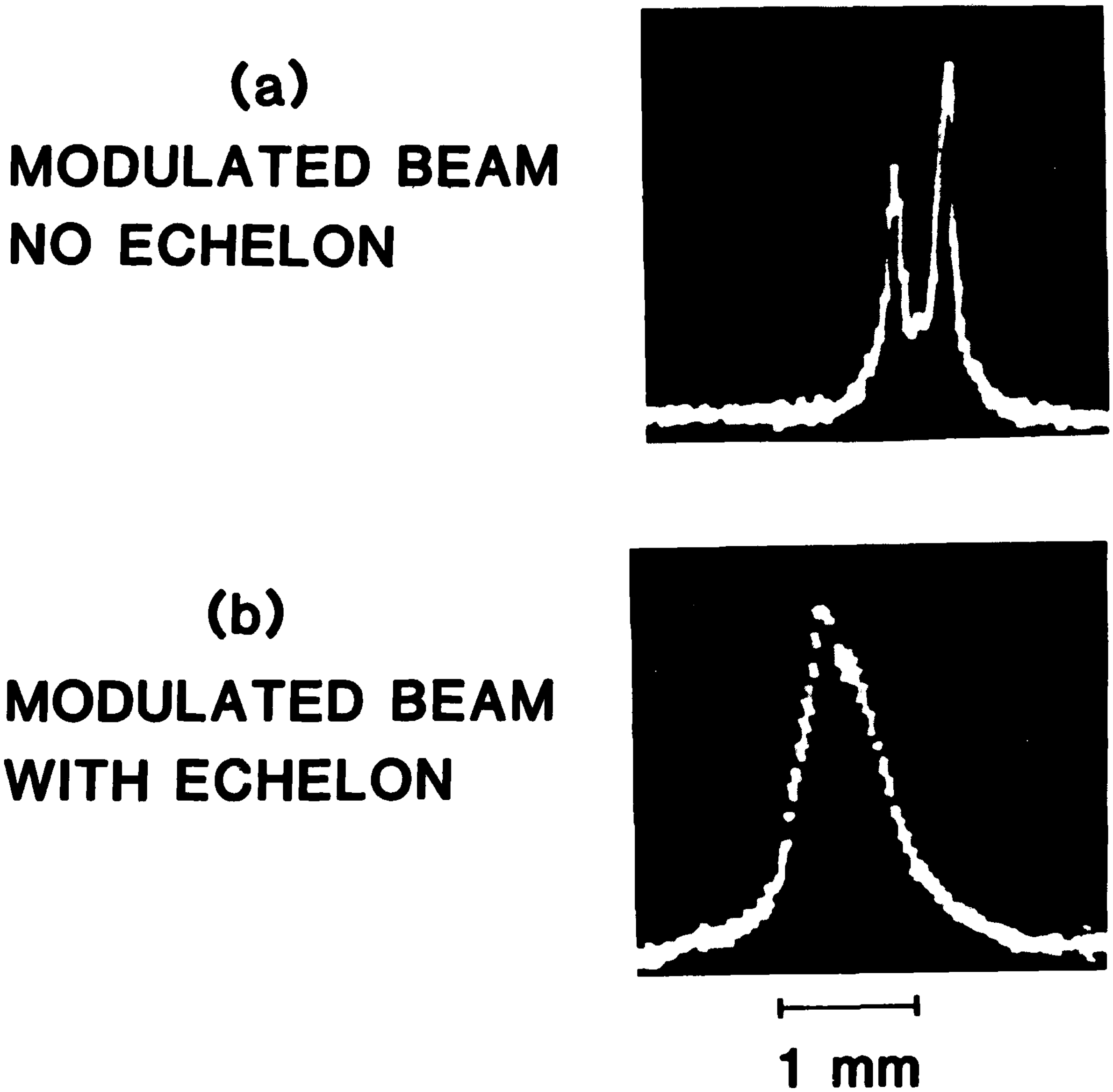

Fig. 4 — Quasi-near field focal profiles obtained without (a) and with (b) the echelon. In both cases the laser beam at the lens had the same structured profile.

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